RESPIRATION OF OXYGEN AT HIGH PRESSURE, FEATURES OF AND TRAINING FOR SUCH RESPIRATION AND THE PHYSIOLOGICAL BASIS

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In a preceding article [4] we showed that the so-called reserve time of man at high altitudes is so small that it does not answer the safety requirements for high-altitude and space flight. According to our data, if the oxygen supply is cut off, the reserve time of a pilot and astronaut at an altitude of 9000 m is numbered in minutes, and in seconds beginning at an altitude of 10,000 m. As our investigations in a pressure chamber have demonstrated, when a spacecraft cabin is depressurized at altitudes greater than 13,000 m, the crew is in danger of quick loss of consciousness, regardless whether pure oxygen is being breathed or not. The reason for loss of consciousness under such conditions is the abrupt drop in partial oxygen pressure in the inhaled and aleveolar air and blood deoxygenation, typical for such altitudes, i.e., losses in oxygen reserves through the lungs.

The results of a study of the problem of the reserve time of a human being in the entire range of flight altitudes and especially the strikingly small values at high altitudes were the reason for further search for effective ways and means which might substantially increase the reserve time of a pilot and astronaut in an emergency situation at high altitudes.

The positive role of carbon dioxide in preventive treatment of oxygen deficiency has been widely emphasized in the literature, and suggestions have been made that the respiration of carbogene may considerable strengthen the high-altitude stability of the human organism to oxygen deficiency at high altitudes [2-8, 12]. It was demonstrated by us experimentally that when breathing carbogene at altitudes of 13,500 m and above no increase in reserve time is achieved; in fact, deterioration was observed in a number of cases as compared with the respiration of pure oxygen.

The basic reason for the loss in human efficiency and for the sharp deterioration of his general state and well-being when breathing carbogene *was the onset of acute oxygen deficiency, which represented a direct threat to his life [5]. /238

It has become obvious that it is possible to maintain satisfactory efficiency of a pilot and astronaut and to prevent loss of consciousness when the cabin is depressurized at great altitudes only by ensuring a sufficient oxygen supply for the human organism in such an emergency situation.

In this connection the idea has arisen of supplying oxygen to the respiratory tracts of man under increased pressure.

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*Translator's Note: Oxygen with admixture of CO_2.

Tests of the new method of breathing and of test samples of oxygen devices have yielded encouraging results. Despite fixed preconceived views, it has been found that it is possible to breathe for sometime when there is considerable resistance to expiration [11].

Tests of this method of breathing have shown that an increase of 15-25 mm Hg oxygen pressure raises the ceiling for a pilot. At such values of pressure, altitudes of 15,200 m can be reached and maintained for 3-5 minutes.

Pilots using this method of breathing have given positive reports and have remarked that they are less fatigued than when they had to use oxygen equipment of the usual type.

The new method of breathing has proved to be a highly effective measure in raising the oxygen supply of the organism at high altitudes.

In the opinion of other authors the factors limiting the application of respiration at increased pressure may be negative psychological moments (fear) and disruption of the blood circulation. Judging from our experiment, however, the training program we introduced for breathing at increased pressure leads to the development of adaptation by the organism to the unusual breathing and to restructuring of the respiration process: unpleasant subjective sensations are considerably weakened or disappear entirely. Insofar as circulatory disorders are concerned, the use of excess pressure of 2032 mm Hg at altitudes of up to 13,706 m do not cause noticeable derangements of blood circulation.

When the excess oxygen and the altitude of climb are further increased, serious disruptions in blood circulation may appear, going so far as collapse or fainting. Although the contingent of flying personnel and astronauts is selected from among candidates distinguished by a superior cardiovascular system, it is not permissible to fail to allow for the possibility of serious disorders in blood circulation at high excess pressures at maximum altitudes. In fact it can be easily imagined that one-sided increase of the excess pressure in the closed system of oxygen equipment and lungs may lead to a considerable increase in the intrapulmonic and intrathoracic pressure. The major venous channels may be contracted: the suction action of the thorax during inspiration may become /239
sharply attenuated. If the cardiac muscle is relatively weak, the return of blood to the right ventricle may decrease, resulting in a reduction of the blood volume per minute and per beat, thus sharply changing the well-being and the general status of the test subject for the worse. Judging by our data as well as by those of other authors, such cases occur comparatively infrequently, since it has been found that when breathing at increased pressure the blood pressure also increases, although to a lesser extent as compared with that of the excess oxygen pressure used in the space beneath the mask [11]. It is urgently recommended that high-pressure respiration be combined with the use of external compensatory equipment in the form of a special high-altitude compensation suit [9, 10].

Application of the new method of breathing oxygen at increased pressure is accomplished in two ways. In the first way the excess oxygen pressure in the closed system is maintained constant during the entire respiratory cycle; the intrapulmonic pressure is kept continuously at a higher level as compared with the ambient atmospheric pressure. In the other method, respiration is accom-

plished with variable pressure at various phases of the respiratory cycle. The excess oxygen pressure is produced only in the inspiration phase, and expiration is accomplished either freely, when the excess pressure is completely ejected, or during expiration and the respiratory pause only a part of the excess pressure is ejected to reduce the resistance to respiration at the most difficult moment—in the expiration phase. At the present time it is still difficult to say which of these two methods of breathing oxygen under increased pressure should be preferred.

In our opinion, respiration of oxygen under continuous constant pressure has a considerable advantage over respiration under variable, non-constant pressure.

When breathing oxygen under increased constant pressure, it is easier to keep the partial oxygen pressure in the expired and alevolar air at a stable and necessary level; which is the main purpose for breathing oxygen at increased pressure. Moreover, the organism adapts more readily to constant, invariable conditions. Pressure constancy in a closed system eliminates the unpleasant subjective sensations of labored respiration which exists in man when the upper respiratory tracts are irritated by pressure fluctuations.

A major drawback of breathing oxygen at increased constant pressure is the unrelieved stress on the respiratory musculature, particularly on the muscular apparatus of inspiration, which remains in a state of continuous tonic contraction. /240
This continuous static work of the respiratory musculature causes constant human stress and strain in breathing oxygen under increased pressure and rapidly leads to depression of respiration and general fatigue. In the opinion of some authors, the rapid onset of fatigue during static work is due to the prolonged and continuous process of excitation in the central nervous system as a result of the continuous flux of afferent pulses from the working muscles, as well as being due to difficulties of blood circulation in the muscles. All this leads to a restriction of the oxygen supply to the muscles and to accumulation of exchange products.

From our viewpoint, it is doubtful whether it should be considered expedient to put the oxygen under pressure only during the inspiration phase with the desire of eliminating labored resistance to expiration. An essential drawback to this method of respiration with alternating pressure is primarily that application of increased pressure during the expiration phase and the respiratory pause negates the advantage of breathing oxygen at increased pressure, because during the expiration phase and the respiratory pause the blood again is saturated when the oxygen pressure in the alveolar air is equal to the pressure of the ambient atmosphere. Consequently, this method of breathing cannot guarantee a constant level of partial oxygen pressure in the alveolar air.

The suggestion that the amount of excess oxygen pressure be considerably increased during the inspiration phase so as to raise the mean partial oxygen pressure in the alveolar air cannot be adopted, since hyperventilation of the lungs, which would occur in this case, may lead to substantial erosion of CO_2 and, consequently, to a dangerous degree of hypocapnia.

Of considerable interest is the respiration of oxygen at increased pressure not with complete interruption of pressure in the expiration phase, but only during some portion of it, which would have to be determined experimentally.

All researchers into the problem of breathing oxygen under increased pressure know quite well that even in this case, when we apply respiration of oxygen at constant pressure, it is impossible to prevent the excess oxygen pressure in the space under the mask, and therefore in the lungs, from dropping during the inspiration phase, when the chest cavity expands. On the other hand, during expiration it increases. Consequently, there are slight fluctuations in excess oxygen pressure even when breathing under constant pressure. They depend on variations in the capacity of the chest cavity during the in- and expiration phases.

Taking the constant stress and strain of the human being into account, due to static strain on the basic and auxiliary respiratory musculature while breathing oxygen under constant high pressure, aggravated by the static strain on the skeletal musculature due to the tightening and continuous compressing high-altitude compensation suit, it is necessary to think about reducing the constant stress and strain on the pilot by allotting him brief periods of rest during the individual phases of the respiration cycle. Such short-term periods of rest during the individual respiratory phases can be achieved by partial interruption of the excess oxygen pressure in the space under the mask as well as in the chambers of the tightening device of the high-altitude compensation suit. The magnitude of such partial interruption of the excess oxygen pressure in the mask space and in the chambers of the tightening device must not exceed the value at which acute hypoxia or hypocapnia may arise. It must be completely sufficient to remove, completely or partially, the stress and strain on the pilot during these rest periods. /241

With such variable pressure and partial interruption of the oxygen pressure under the mask and in the chambers of the tightening device of the high-altitude suit, it is possible to reduce the stress and the overall strain, which sharply limit the time of exposure of a pilot and astronaut at high altitudes when breathing oxygen under increased pressure. In this case we can hope for an improvement in the supply of blood to the respiratory and skeletal musculature and for attenuation of the flux of afferent signals into the central nervous system, and therefore for better altitude endurance and longer exposure time for pilots and astronauts when breathing oxygen with alternating increased pressure.

Such, in general outlines, are the purpose, approaches and methods of applying oxygen respiration under increased pressure in aviation and astronautics. In the experiments we conducted, the use of the new method of breathing oxygen under very high pressure increased the reserve time of a human being by several factors in an emergency situation at altitudes of more than 13,000 m and gave him the capability of emergency descent with an airplane to a safe altitude. It must be immediately emphasized, however, that positive results can be realized with the new breathing method only when the process of learning the unusual and difficult method of breathing with appreciable resistance to expiration is correctly organized, when the techniques and rules of use of the oxygen equipment are thoroughly known, when the special high-altitude gear is correctly chosen and thoroughly adjusted, and when the flying personnel is given rational preparatory training in breathing oxygen under increased pressure.

Teaching and training flying personnel and astronauts to breathe oxygen under increased pressure are the most important of the conditions enumerated above.

There are various opinions on the problem at hand. The aim of the present /242
paper is to examine, in the light of aviation and space medicine, the physiological prerequisites that must be taken into account in developing a rational schedule for training flying personnel and astronauts to breathe oxygen under increased pressure.

Respiration of oxygen under increased pressure when there is considerable resistance to expiration is at first unpleasant and is painfully endured by a human being, especially when the uncompensated excess pressure is at maximum values (25-30 mm Hg). But repeated systematic training leads to development of adaptation to this method. In each of our test subjects we observed the process of adaptation of the organism to respiration of oxygen under increased pressure, in the form of a number of high-altitude exercises with gradual increase in the magnitude of the excess oxygen pressure under the mask and in the altitude of climb in each successive exercise. Our suggestion concerning the expediency and necessity of introducing preparatory training for respiration of oxygen under increased pressure was based on the fact, widely known in the field of physiology, that the repeated systematic action of any stimulus leads to the evolution of adaptation, resulting in the appearance and development of new coordinational relationships in the central nervous system and its higher organs and, in the final account, attenuating the action of the stimulus. Sometimes the organism ceases to react to the stimulus altogether.

On the other hand, we know that the cerebral cortex has direct effects on the processes of respiration and blood circulation.

When breathing under increased pressure, strong unusual fluxes of afferent pulses are transmitted to the central nervous system as a result of stimulation of the receptors of the respiratory and cardiovascular systems as well as of the respiratory musculature and organs of the bust cavity. It has been found that these pulses inhibit respiration by reflex, leading to a reduction in blood pressure and to damping of the cardiac activity.

Respiration under increased pressure leads to functional disorders in the respiration and blood-circulation processes which are proportional to the magni- /243
tude of the excess oxygen pressure in the space under the mask. The maximum value of the excess (uncompensated) pressure that can be endured by the human organism is 25 mm Hg. Even in this case, however, the act of respiration and the process of blood circulation are not immediately normalized, but only gradually during the process of adaptation of the organism as a result of restructuring of the coordinational relations in the central nervous system often a number of repeated exercizes, increasing in difficulty, while breathing oxygen under increased pressure. The magnitude of the uncompensated excess pressure of 30 mm Hg represents a limit on the compensatory capabilities and is no longer endurable by the human organism, either with high-altitude or ground exercizes, while breathing oxygen under increased pressure (A.P. Apollonov, M.I. Vakar, P.K. Isakov, et al.).

On the other hand, the investigations we made in 1950 on the partial pressure of gases in the alveolar air when breathing oxygen under increased pressure revealed a considerable decrease in the partial O_2 and CO_2 pressure, especially at those altitudes which are the limit of application of oxygen equipment with excess pressure. The partial oxygen pressure in alveolar air at an altitude of 15,000 m (using an oxygen system of the KP-28 type) fluctuated within the limits of 37-48 mm Hg and came close to its critical level (about 30 mm Hg), which is the hypoxia limit that is unendurable to the human organism. The partial CO_2 pressure at the same altitude fluctuated in the range 20-26 mm Hg, which also comes close to the critical hypocapnia limit.

Our studies revealed the dangerous effect of hypoxia and hypocapnia whenever the partial oxygen pressure in alveolar air dropped below the limits of 40 mm Hg and the partial CO_2 pressure below 20 mm Hg while untrained personnel breathed oxygen under increased pressure.

Thus, when breathing oxygen under increased pressure, the human organism is subjected to the complex effect of strong and unusual stimuli. Among these the most important are the excess pressure itself, hypoxia and hypocapnia. All these factors, or each of them separately, when they reach an extraordinary level, may become the leading factor in the negative effect of altitude on the human organism. It is obvious that either of the three, excess pressure, hypoxia or hypocapnia, may play a negative part in the genesis of functional disruptions of the organism at high altitudes, the negative effect being aggravated when all three exert a simultaneous effect on the organism.

Of major importance in the complex effect is apparently the factor which, under given concrete conditions, first reaches the level at which it is critical for the organism. Besides the major active factors we cannot underrate the /244
significance of the effect of the very factor of air rarefaction and of the resultant effects, namely, decompression phenomena, tension of the nervous-psychic type during tests in a pressure chamber or in high-altitude flight, and the appreciable static muscular work involved in using sets of oxygen equipment while tightly laced up in a high-altitude suit. All this complicates pilot activity and aggravates the effect of the major active factors on the human organism while breathing oxygen under increased pressure.

A negative psychological outlook and the volitional qualities of the examinee, who may or may not be capable of supressing the adverse moments (fear, lack of confidence in the equipment, in oneself, uncertainty of one's capabilities, etc.), are of considerable significance, especially during the first exercises and climb operations while breathing oxygen at high pressures. This negative aspect may be the reason not only for changes in the activity of a number of organs and systems, but may also cause or aggravate the evolution and duration of a number of adverse, purely vegetative reactions, leading to deterioration in the well-being and overall state of the test subjects' organism while breathing oxygen at increased pressure (retardation of pulse rate, paleness, cold sweat, collapse, incipient fainting state or fainting state). Consequently, a negative psychological outlook may in itself be the only reason for failure to endure altitude and respiration under high pressure.

This brief examination of all the physical, physiological and psychic factors of oxygen respiration at high pressure was intended to demonstrate that the new method of respiration lays an additional strain on the human organism and places it in the unusual conditions of existence at high altitudes. In particular, demands are made on the functional state of the nervous-psychic sphere and on the activity of the cardiovascular system and of respiration.

By analyzing all cases of abrupt deterioration of the well-being and state of the human organism, of spastic seizures and of fainting at high altitudes when breathing oxygen at high pressure on the part of our test subjects, we found that such events occurred, as a rule, during the first exercises, or during repeated exercizes only when they were applied at an altitude greater than the magnitude of the excess oxygen pressure or when the partial O_2 and CO_2 pressure in the alveolar air dropped to the critical level. Sometimes a sharp deterioration in well-being at high altitudes set in because of psychogenic instability. It was obvious that familiarization climbing operations alone are not sufficient for introducing the new breathing method.

Unusual respiration with considerable resistance to expiration led to transformation of the normal breathing act and to disruption of the normal blood-circulation processes (retardation in blood flow, stagnation phenomena in the major and minor blood-circulation channels). On the other hand, the detection of pronounced degrees of anoxia and hypocapnia when breathing under high pressure, particularly at high altitudes, inevitably compelled the researchers to believe that it was necessary to carry out special preliminary training of the flying personnel to breathe oxygen at high pressure, with gradual, consistent accommodation to ever higher values of excess oxygen pressure and of climb-altitude. With repreated exercizes breathing oxygen at increased pressure the test subjects, as a result of functional restructuring, were observed to adapt, to accustom the organism not only to excess pressure, but also to hypoxia and hypocapnia, if their intensity does not surpass the critical level. /245

According to our data, in order to evolve a new stereotype of respiration and adaptation by the organism to hypoxia and hypocapnia, five to seven high-altitude training exercises are necessary, with gradual accommodation to progressively higher altitudes and increase in magnitude of the excess pressure. The time of exposition at each altitude must be no less than 10-15 min, with the condition, of course, that the test subjects exhibit satisfactory endurance and comfort. It is possible, in principle, to reduce the number of sessions, but to do so it is necessary to increase the time of exposure of the test subject at any given altitude.

Psychological adaptation also sets in during the process of preliminary training, accompanied by successive and constant accommodation to increasing values of excess oxygen pressure and climb altitude.

Training for respiration of oxygen under increased pressure must be carried out taking the individual characteristics of the test subject's organism into account. In some cases it is possible to reduce the number of training sessions, and in other cases a larger number may be required to reach the desired effect. Deliberate, unreasoned reduction of the number of training sessions may lead to serious functional disorders, even to collapse or fainting.

At the present time special training of flying personnel in a pressure chamber with successive accommodation to high altitudes and increasingly high values of excess oxygen pressure is acknowledged to be the necessary condition for achieving high efficiency in the use of high-pressure oxygen respiration in flight at high altitudes.

On the basis of all that has been said above, as well as on the basis of experience gained in training flying personnel to breathe oxygen at extremely high pressure, it has become obvious that further development of a rational training /246
schedule must be based on the physiological characteristics of high-pressure oxygen respiration, taking into account all the factors that might have a negative effect on the human organism under such conditions (oxygen deficiency, excess pressure, hypocapnia, decompression phenomena, negative psychogenic moments, etc.).

Suggestions that successive high-altitude training of flying personnel to high-pressure oxygen respiration be replaced by two - three familiarization climbing operations in a pressure chamber or that such training be limited in general only to ground exercises must be rejected as scientifically unfounded.

Consecutive preliminary training of flying personnel and astronauts for high-pressure oxygen respiration, for gradually increasing values of excess oxygen pressure in the inspired air and of climb altitude, has, as its primary aim, the development of the human organism to adapt to all the active factors in such a situation. Such adaptation is achieved with a specific number of training sessions and sufficient exposition time.

Familiarization climbs or ground exercises alone have a different purpose and cannot bring about adaptation of the organism to the extent necessary for successful mastery of the new breathing method.

During the process of training in the new respiration method familiarization climbing operations and ground exercises as well as the showing of special training films demonstrating the new oxygen equipment and the rules for using it are necessary stages in the accommodation process. Moreover, ground exercises and familiarization climbs may be the initial link in the process of training flight personnel and astronauts in high-pressure oxygen respiration.

In real flight conditions, however, the simultaneous complex effect of all the active factors on the human organism is characteristic. Consequently, a rationally designed training schedule must, or completely as possible, take in this complex of stimuli in order to approximate the real conditions of high-altitudes and space flight.

In our opinion, the training schedule should expediently provide for a final exercise at maximum altitude at maximum values of excess oxygen pressure and, in contrast with all the other preceding exercises, should be carried out with an abrupt drop of barometric pressure within the chamber. This exercise would imitate the conditions of sudden depressurization of the cabin in high altitude and space flight and might make it possible to objectively evaluate the effectiveness of the entire preliminary training of pilots and astronauts in high-pressure oxy- /247
gen breathing.

According to our data, high-pressure oxygen respiration, complicated by a rapid, abrupt drop in atmospheric pressure, is a serious ordeal for an untrained organism. In such cases circulatory collapse and fainting have sometimes been observed.

As technical progress is made in developing the new type oxygen-respiration equipment and compensating suits it is not impossible that a certain improvement will be achieved in supplying oxygen to the organism and in damping the deleterious effect of the other factors. But we will not succeed in eliminating such deleterious effects to the same extent as achieved using a high-altitude emergency suit.

Even with the most perfect model of a high-altitude suit we will not be able to achieve uniform distribution of pressure over any part of the human body. But the nonuniform pressure distribution exerted on the human body by a high-altitude-compensation suit is the source of uncompensated excess pressure which, in turn, is accompanied by a certain degree of hypoxia and hypocapnia. And therefore even in this case it is necessary to conduct preliminary persistent training of flight personnel and astronauts in breathing oxygen under high pressure so as to adapt the organism to the unfavorable factors.

In conclusion we would emphasize once again that the development of a rational training schedule for flight personnel and astronauts in breathing oxygen at increased pressure, taking the physiological role of all the active factors into account, will help the flying personnel to accommodate faster to the new breathing method and to the new oxygen equipment sets in aircraft and will permit such personnel to make life-saving descents in an emergency situation at high altitudes during aviation and space flights.

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